NMMA : nuclear-physics and multi-messenger astrophysics framework

Pang P. T. H., et al., 2023, Nature Communications., 14, 8352

Credit: Tohoku University

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New insights

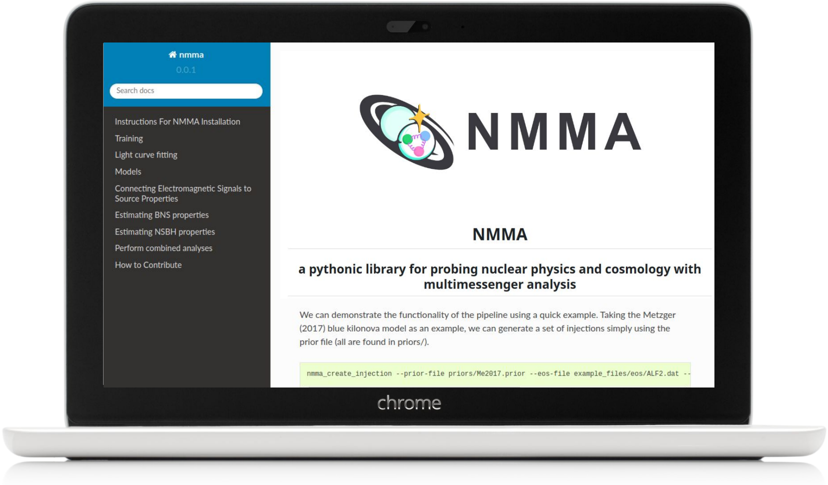
→ constrained nuclear EOS

→ confirmed predictions of General Relativity

→ production site of heavy elements

→ alternative method to infer the expansion rate of the Universe

NMMA | Functionalities



Github: https://github.com/nuclear-multimessenger-astronomy/nmma

Bayesian inference

- observational data & injections
- gravitational-wave signals
- electromagnetic signals
- joint inference of GW+ EM signals

Including nuclear physics

- neutron star equation of state (EOS)

Estimating binary source properties

- Binary neutron star (BNS)
- Neutron star black hole (NSBH)

Other

- estimating the Hubble Constant

Bayesian inference

Parameter estimation through **Bayes theorem**

Likelihood *Prior*

$$p(\vec{\theta}|d,\mathcal{H}) \equiv \frac{\mathcal{L}(\vec{\theta})\pi(\vec{\theta})}{\mathcal{Z}}$$

Probability of the hypothesis given the data

Evidence

Gravitational-wave inference | Bilby

Ashton, et al. (2019)

$$\mathcal{L}_{GW} \propto \exp\left(-\frac{1}{2}\langle d - h(\vec{\theta})|d - h(\vec{\theta})\rangle\right)$$

Electromagnetic inference | NMMA

Pang et al. (2023)

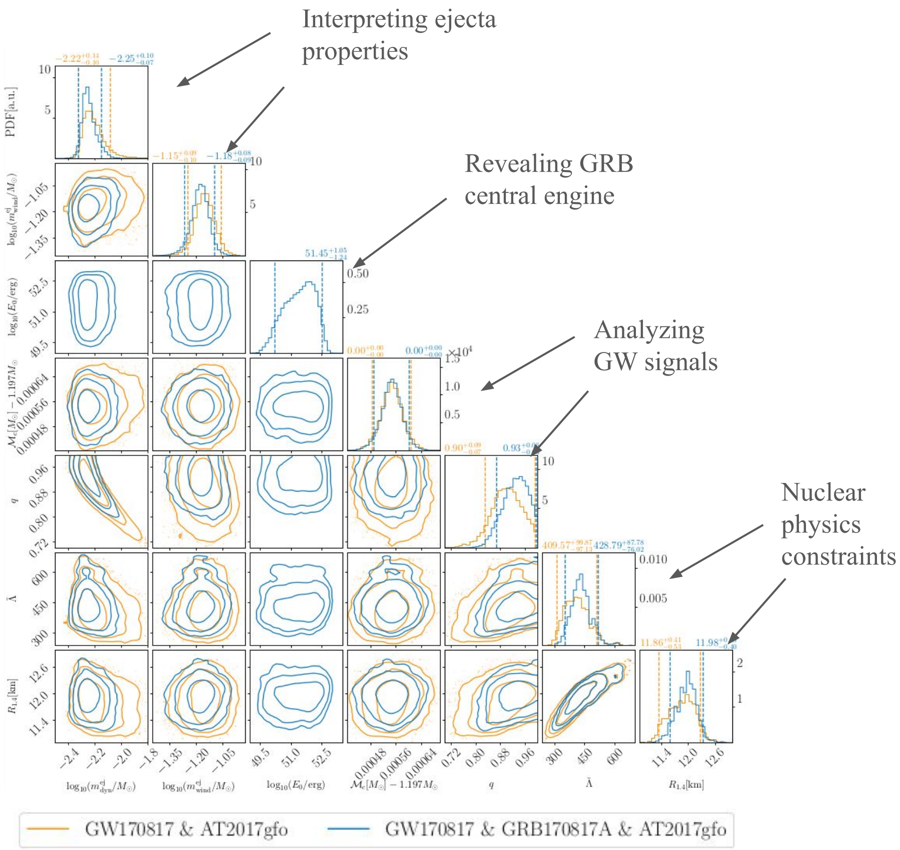
$$\mathcal{L}_{EM} \propto \exp\left(-\frac{1}{2}\sum_{ij}\frac{(m_i^j - m_i^{\mathrm{j,est}}(\vec{\theta}))^2}{(\sigma_{i,\mathrm{stat}}^j)^2 + \sigma_{\mathrm{sys}}^2}\right)$$

Joint inference | NMMA

Pang et al. (2023)

$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{GW}(\vec{\theta}_{GW}) \times \mathcal{L}_{EM}(\vec{\theta}_{EM})$$

Bayesian inference



Pang et al. (2023)

Science case: Pang et al. 2023 | **NMMA**

- GW170817 + GRB170817A + AT2017gfo

$$\mathcal{L}(\vec{\theta}) = \mathcal{L}_{GW}(\vec{\theta}_{GW}) \times \mathcal{L}_{EM}(\vec{\theta}_{EM})$$

- including nuclear physics information | EOS

Models

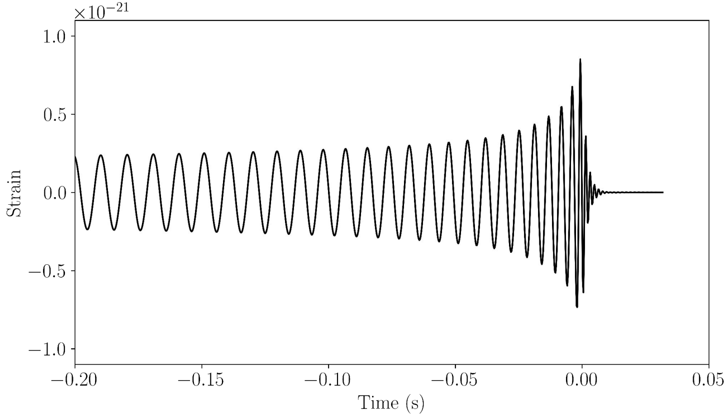
Grationational waveform models

- Gravitational waveform in time domain

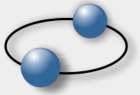
$$h(t) = A(t)e^{-i\Psi(t)}$$

Phase

Amplitude



BNS sources

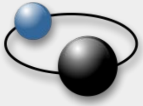


Post-Newtonian models
- TaylorF2

Effective-One-Body models
- SEOBNRv4_ROM_NRTidal

Phenomenological models
- PhenomD_NRTidal,
- PhenomPv2_NRTidal(v2, v3 | Abac at al. 2023)

NSBH sources



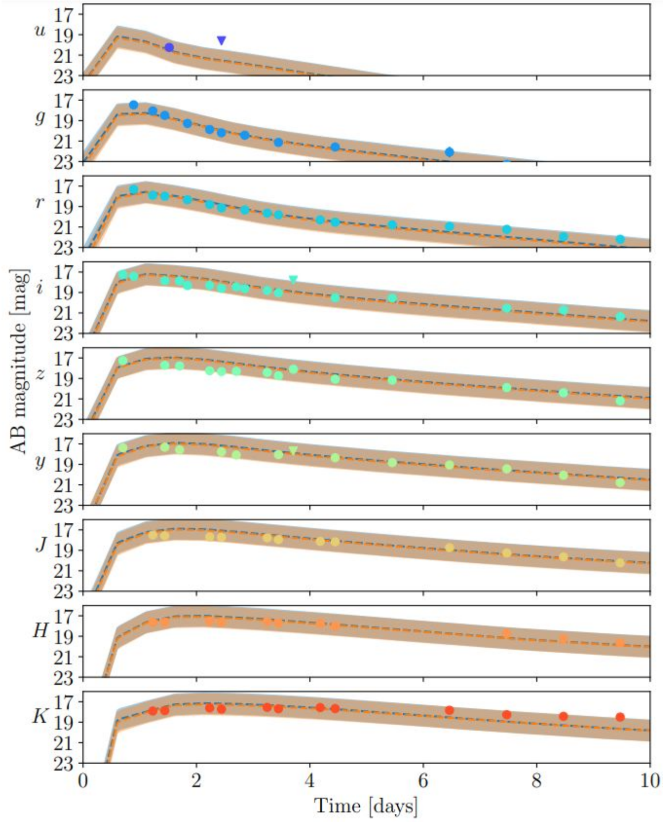
Phenomenological models
- IMRPhenomNSBH
- SEOBNRv4 ROM NRTidalv2_NSBH

All GW models are enabled with: **LALsimulation**

(LIGO Scientific Collaboration, Algorithm Library LALsuite)

Models

Best-fit light curves | GW170817+GRB170817A+AT2017gfo



Pang et al. (2023)

Electromagnetic (EM) transient models

Gamma-ray burst afterglow

- **afterglowpy** | Van Eerten et al. (2010), Ryan et al. (2020)
- soon: **Pyblastafterglow** | Nedora et al. (2021)

Kilonovae

- analytic models
- models based on radiative transfer simulations (POSSIS, Kasen et al.)

Supernovae

- SN models in **sncosmo** | (Levan et al. 2005)

Models

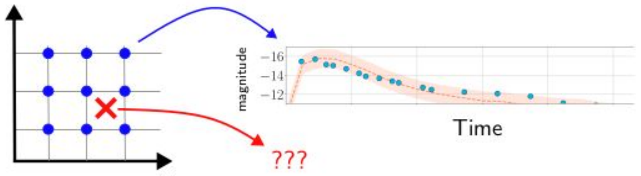
Kilonovae

- **radiative transfer simulation models**

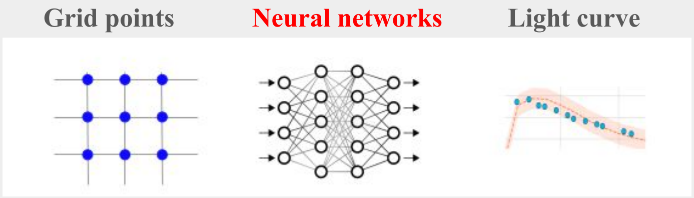
e.g. POSSIS

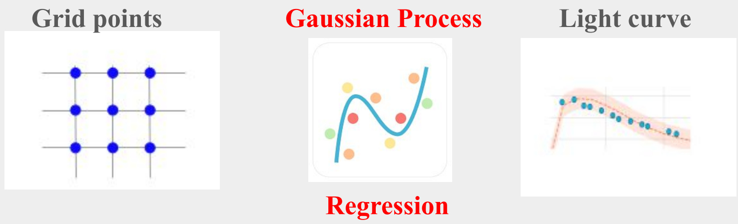
→ simulation at grid points provide light curves

→ light curve at arbitrary parameter values arise from surrogate models



Methods | EM transient models





Including nuclear physics

- use nuclear physics models to obtain

Equation-of-state

$\downarrow$

- mass m,
- radius R,
- tidal deformability Λ

- sample on EOS during parameter estimation

Prior

$m_{1,2}$

$\downarrow$

Interpolate

$$p(\Lambda_i|m_i, \mathrm{EOS}) = \delta(\Lambda_\mathrm{i} - \Lambda(\mathrm{m_i}; \mathrm{EOS}))$$

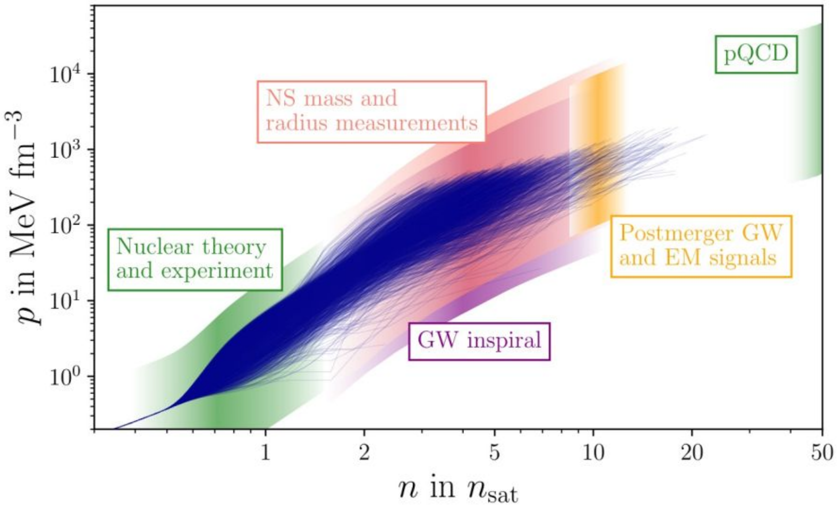
$\downarrow$

GW waveform

$$h(t; m_{1,2}, \Lambda_{1,2}, \vec{\theta})$$

Including nuclear physics

Constraints on the EOS from different research fields



Koehn et. al. (2024)

arXiv:2402.04172v1

Science case: Study of Koehn et al. 2024

Employed constraints

Nuclear

- Chiral EFT
- pQCD
- PREX-II
- CREX
- Heavy ion collisions

Isolated neutron stars

- Heavy pulsars
- NICER
- HESS object
- qLMXBs
- Thermo-nuclear accretion bursts

Binary neutron stars

- GW170817 + AT2017gfo + GRB170817A
- GW190425
- GRB211211A
- Post-merger constraint from GW170817

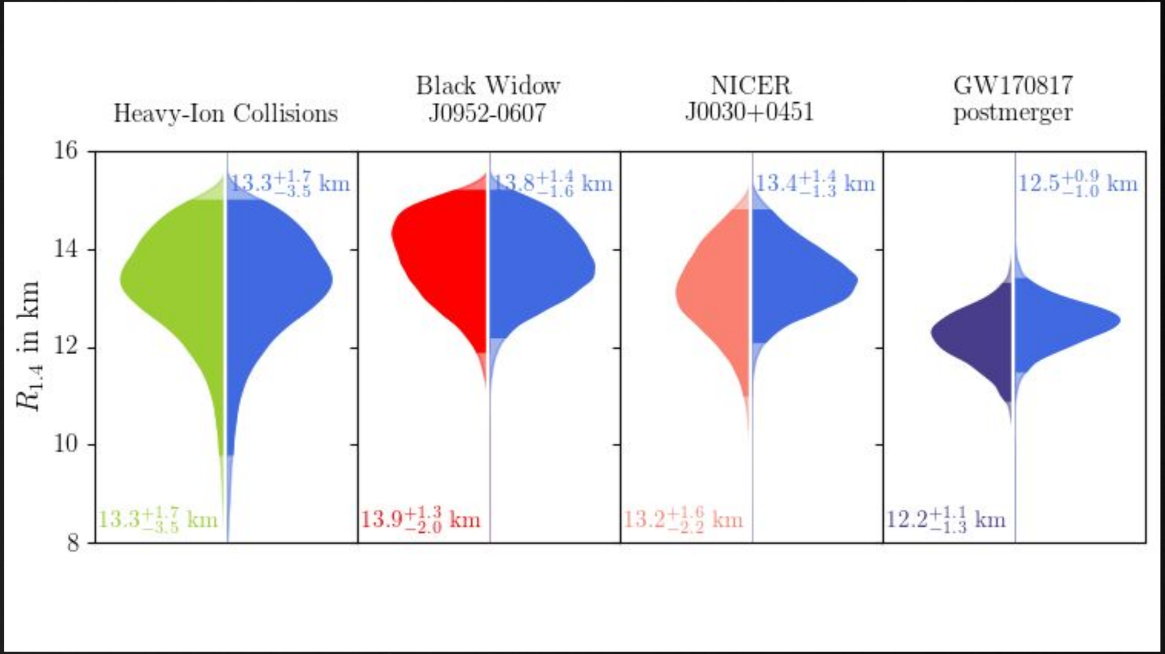
Combining different constraints on the EOS from different research fields

Science case:

Koehn et al. 2024

arXiv:2402.04172v1

Combining different constraints on the EOS from different research fields



Science case:

Koehn et al. 2024

arXiv:2402.04172v1

Check out our

Nuclear constraint App!

Bayesian inference

Hypothesis testing using **Bayes theorem**

$$\frac{p(\mathcal{H}_1|d, I)}{p(\mathcal{H}_2|d, I)} = \frac{p(d|\mathcal{H}_1, I)p(\mathcal{H}_1|I)}{p(d|\mathcal{H}_2, I)p(\mathcal{H}_2|I)}$$

$$\downarrow \qquad\qquad \downarrow \qquad\qquad \downarrow$$

$$\mathcal{O}_2^1 = \mathcal{B}_2^1 \times \Pi_2^1$$

Odds ratio *Bayes factor* *Prior Odds*

→ investigate the plausibility of competing models

Application: model selection

Interpreting: Bayes Factors

$\ln[\mathcal{B}^1_{\mathrm{ref}}] < -4.61$ | decisive evidence

$-4.61 \leq \ln[\mathcal{B}^1_{\mathrm{ref}}] \leq -2.30$ | strong evidence

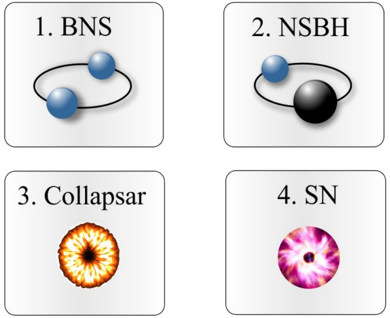
$-2.30 \leq \ln[\mathcal{B}^1_{\mathrm{ref}}] \leq -1.10$ | substantial evidence

$-1.10 \leq \ln[\mathcal{B}^1_{\mathrm{ref}}] \leq 0$ | no strong evidence

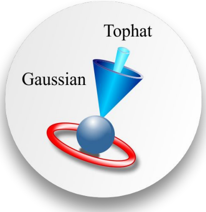
Bayesian inference

Studying the origin of GRB211211A

possible scenarios



possible GRB jet types



Science case: Study of Kunert et al. 2023

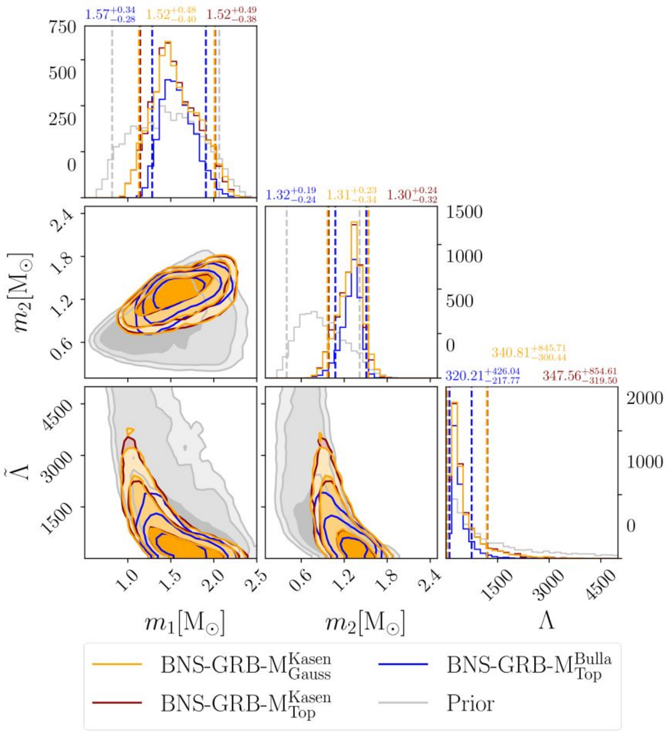
Results: Bayes factors

Name	Astrophysical Processes	GRB Jet Structure	Model dimension	Bayes factor $\ln[\mathcal{B}^{1}_{\mathrm{ref}}]$
BNS-GRB-$\mathrm{M}^{\mathrm{Kasen}}_{\mathrm{top}}$	Kilonova + GRB	Tophat	11	ref.
BNS-GRB-$\mathrm{M}^{\mathrm{Kasen}}_{\mathrm{Gauss}}$	Kilonova + GRB	Gaussian	12	-1.21 ± 0.12
BNS-GRB-$\mathrm{M}^{\mathrm{Bulla}}_{\mathrm{top}}$	Kilonova + GRB	Tophat	11	-4.51 ± 0.12
BNS-GRB-$\mathrm{M}^{\mathrm{Bulla}}_{\mathrm{Gauss}}$	Kilonova + GRB	Gaussian	12	-6.26 ± 0.12
NSBH-GRB-$\mathrm{M}_{\mathrm{top}}$	Kilonova + GRB	Tophat	11	-8.41 ± 0.12
NSBH-GRB-$\mathrm{M}_{\mathrm{Gauss}}$	Kilonova + GRB	Gaussian	12	-10.56 ± 0.12
SNCol-GRB-$\mathrm{M}_{\mathrm{top}}$	rCCSNe + GRB	Tophat	14	-15.24 ± 0.13
SNCol-GRB-$\mathrm{M}_{\mathrm{Gauss}}$	rCCSNe + GRB	Gaussian	15	-16.97 ± 0.13
SN98bw-GRB-$\mathrm{M}_{\mathrm{top}}$	CCSNe + GRB	Tophat	8	-12.66 ± 0.12
SN98bw-GRB-$\mathrm{M}_{\mathrm{Gauss}}$	CCSNe + GRB	Gaussian	9	-12.59 ± 0.12
GRB-$\mathrm{M}_{\mathrm{top}}$	GRB	Tophat	8	-12.47 ± 0.12
GRB-$\mathrm{M}_{\mathrm{Gauss}}$	GRB	Gaussian	9	-12.65 ± 0.12

Kunert et al. (2023)

Connecting electromagnetic signals to binary properties

BNS properties of GRB211211A



Kunert et al. (2023)

BNS sources | phenomenological relations

- relation of **dynamical ejecta mass** | [Krueger & Foucart, (2020)]

$$\frac{m^{\rm ej}_{\rm dyn,fit}}{10^{-3}M_\odot} = \left(\frac{a}{C_1} + b\left(\frac{m_2}{m_1}\right)^n + cC_1\right) + (1 \leftrightarrow 2)$$

- relation of **disk mass** | [Dietrich et al., (2020)]

$$\log_{10}\left(\frac{m_{\rm disk}}{M_\odot}\right) = \max\left(-3, a\left(1 + b\tanh\left(\frac{c-(m_1+m_2)M^{-1}_{\rm threshold}}{d}\right)\right)\right)$$

Estimate the Hubble Constant

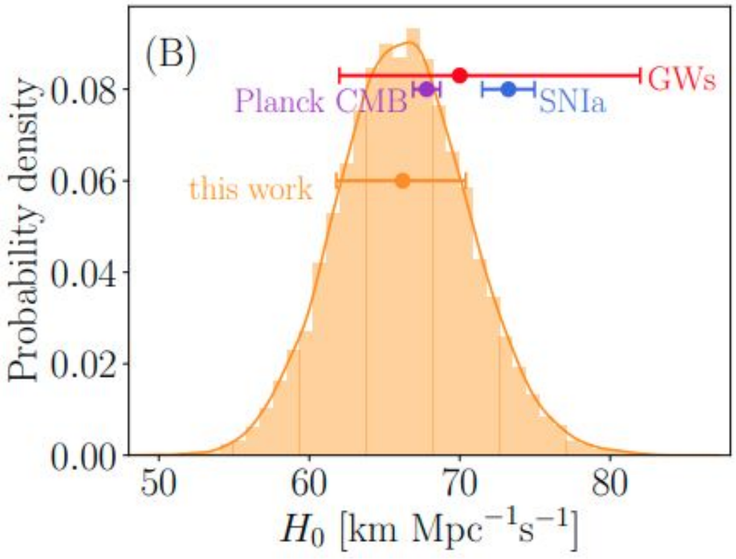
- evaluate linear Hubble relation

$$c \cdot z = v_H = H_0 \cdot D$$

Applications:

- Gravitational-wave standard sirens
- Kilonovae standard candels
- Joint estimates (GW + EM)

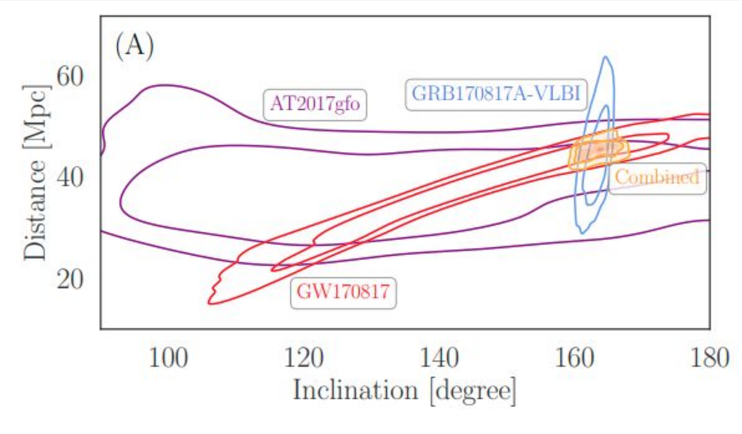
Estimate the Hubble Constant



Dietrich et. al, (2020)

Science case: Study of Dietrich et al. 2020

- use joint estimate of distance from GW170817+GRB170817A+AT2017gfo data



Dietrich et. al, (2020)

Current code developments

- Implementing new GRB model | pyblastafterglow
- Accelerating GW inference
- Sampling on nuclear parameters directly
- **Sampling on dark matter parameters**

> dark matter mass, m_χ

> dark matter fraction, f_χ

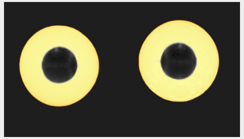
→ requires constructing DM EOS set

Dark matter | Theory

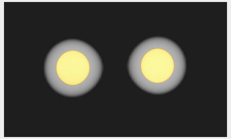
→ Introduction by Violetta Sagun

- simple case: fermionic dark matter
- baryonic and dark matter only interact gravitationally

→ there are 2 possible configurations



Core configuration



Halo configuration

NMMA: worldwide contributions

University Potsdam and Max Planck Institute for Gravitational Physics
- computational astrophysics
- gravitational-wave modelling
- multi-messenger data analysis

University of Minnesota
- optical and near-infrared observations
- multi-messenger data analysis

Observatory of Côte d’Azur
- optical and near-infrared observations
- multi-messenger data analysis

Utrecht University
- gravitational-wave data analysis
- multi-messenger data analysis

University of Ferrara
- modelling of electromagnetic signals

Los Alamos National Lab
- nuclear physics

Observations

Theory

The NMMA collaboration thanks for your attention!